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Solar System Studies

[A report on work done at the Lunar and Planetary Institute: 27 Dec., 96 - 30 March, 97]

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The main research problem that I have pursued during my short stay at LPI was the production of short-lived nuclides by solar energetic particles (SEP) and the possibility that an enhanced flux of SEP from an active early Sun could lead to the production of some of the now-extinct short-lived nuclides that were present in the early solar system. In addition, I utilized this visit to analyze some meteorite samples with the analytical tools available at the Johnson Space Center, interacted with scientists at LPI and JSC, visited several universities for discussions on research problems of mutual interest, gave seminars at LPI, Univ. of Calif., San Diego, Caltech and Washington Univ., St. Louis, and worked on several papers written in collaboration with US scientists. Finally, I attended the 28th LPSC, presented a paper, chaired a session and availed the opportunity to interact with a large number of scientific colleagues. Overall, it was a fruitful and scientifically rewarding experience for me and I look forward to avail similar opportunities in the near future. A brief outline of the work carried out is given below.

I. Production of Short-lived Nuclides by Solar Energetic Particles (SEP)

The presence of several now-extinct short-lived nuclides in the early solar system has been established from isotopic studies of samples from primitive meteorites. Several plausible sources of these nuclides have been proposed. These include stellar sources injecting freshly synthesized nuclei to the proto-solar cloud just prior to its collapse, production by low energy heavy ions interacting with ambient gas in a molecular cloud complex, of which the proto-solar cloud was a part, and production by SEP from an active early Sun interacting with nebular gas and dust. Although the possibility of SEP production of these nuclides has been investigated earlier, most of these efforts took in to account only one of the short-lived nuclide (^{26}Al), did not include all the proton and alpha particle induced reactions of interest, the reaction cross sections were often poorly constrained and the SEP irradiation scenarios were also ad-hoc. In the present approach, I have included all the short-lived nuclides (^{41}Ca, ^{36}Cl, ^{26}Al, and ^{53}Mn), whose presence in the early solar system have been inferred from meteorite data and could be potentially produced by SEP. I have included all the possible proton and alpha particle induced reactions and appropriate cross sections in the calculations, considered an irradiation scenario that favors SEP production and looked for a self-consistent picture. More than 70% of the analytical work was completed prior to my reaching LPI (two of my students are also involved in this work) and I have prepared an abstract after my arrival at LPI for the 28th LPSC, based on these results. Subsequently, most of the calculations were completed and the basic results obtained are:

(i) A flux enhancement factor of ~10^5 is needed compared to contemporary SEP flux to explain the meteorite data on initial $^{26}Al/^{27}Al$ ratio in the early solar system.

(ii) A lower flux enhancement factor of ~10^4 is needed for ^{41}Ca, ^{36}Cl, and ^{53}Mn.

We also note that the initial abundance of ^{53}Mn is not very well constrained, and a lower value of ~10^3 for the enhancement factor can explain the initial ^{53}Mn abundance in solar system inferred from the data on differentiated meteorites. *Note that an irradiation time of ~1 Ma has been considered in obtaining the above enhancement factors.* This factor will go up if the irradiation time is shorter. However, a longer irradiation time will not have much affect (except for ^{53}Mn) as the other nuclides have mean life ≤1Ma and their production will reach the saturation level.

Since co-production of ^{26}Al with any of the other nuclides to match the meteorite data is not possible, one can propose a stellar source for ^{26}Al and a SEP production for the others, notwithstanding the fact that the enhancement factor of ~10^4 is rather large even for a T-Tauri Sun. However, we can rule this out based on a very important piece of information we have obtained in an ongoing collaborative experiment with the Enrico Fermi Institute, Univ. of Chicago (see Item-II), which suggests that the short-lived nuclides ^{26}Al and ^{41}Ca are cogenetic.

Finally, if the lower initial abundance of ^{53}Mn inferred from the data on differentiated meteorite is correct, the lower flux enhancement factor of ~10^3 makes SEP production of this nuclide a distinct possibility. In fact this suggestion made by us was favored by one group from JSC (Nyquist et al.) during their presentation at the 28th LPSC.

Publications:

1. *Production of short-lived nuclides by solar energetic particles in the early solar system.*
   J.N.Goswami, K.K.Marhas and S.Sahijpal, *LPSC 28th*, 439-440, 1997.
   [A full paper will be submitted shortly to a Journal]

II. Combined Studies of K and Mg Isotopic Anomalies in Early Solar System Objects.

I have initiated a collaborative program with scientists at the Enrico Fermi Institute (EFI), Univ. of Chicago, to study isotopic records in refractory phases from primitive meteorites to look for possible correlation in the presence of the two short-lived nuclides ^{26}Al and ^{41}Ca in these phases. The occurrence of refractory hibonite grains in CM and CV chondrites provide an opportunity to carry out such an investigation as the hibonites have both high Ca/K and Al/Mg abundance ratios that allow a combined study of these two isotopes.. The samples were identified at EFI, and the isotopic studies were done by us at PRL, India. As noted in Item-I above, the initial results showed a strong correlation between the presence/absence of these two nuclides.

During my stay at LPI, I have worked on a manuscript that will describe our initial results which rule out the SEP irradiation scenario and favors a single stellar source for both of these short-lived nuclides. I received significant inputs from my colleagues at EFI, Chicago, and have had additional discussion with them during the LPSC and hope to complete this project soon..

In addition a second batch of hibonite grains received from EFI, Chicago, have been thoroughly analyzed by me for their chemical composition using the analytical facilities at the Johnson Space Center, during my stay at LPI. This is necessary to identify the most suitable objects for isotopic studies with the ion probe to be conducted in India after my return from LPI.

Publication:

[The final version of the paper describing the initial results is nearly complete and will be soon submitted to a journal]

III. Other Research Activities

(A) Petrology of the Pipliya Meteorite

A new meteorite, Pipliya, that fell in India during last summer was identified as an Eucrite. Although several aspects of this meteorite (chemistry, formation and irradiation history etc.) have been studied in detail, not much had been done to understand its mineral chemistry and petrology. I took this opportunity to carry out studies of mineral chemistry of this sample using the analytical facility at JSC and advice form experts like Mike Zolensky and Dave Mittlefehldt. The meteorite has some unusually large (up to 500 micron) opaque phases (ilmenite and chromite). The data obtained by me will help us to better understand the petrogenesis of this new eucrite.

(B) Discussions and preparation of manuscripts for publications

During my stay at LPI, I also had extensive interactions with some of my scientific collaborators in USA to finalize a couple of joint work for publication. These include a study of *iodine content in silicate and sulfide phases in chondrules from unequilibrated chondrite using ion microprobe and noble gas laser probe* techniques (collaborators from Univ. of Washington, St. Louis; Univ. of Arizona, Tucson and USGS) and *irradiation records in Antarctic meteorite* (collaborator from Univ. of Calif., Berkeley). Good progress has been made in both cases.

I have had several rounds of discussion with JSC and LPI scientists, particularly with those working in the area of early solar system processes, cosmogenic records in meteorites, and lunar exploration. Several future activities including the writing up of a review article on "Cosmogenic records in Antarctic meteorites" (with D. Bogard of JSC and K. Nishiizumi of Univ. of Calif., Berkeley) have been discussed and some initial spadework has been done by me and we hope to pursue this project in the future.

(C) Visits to Universities

I have utilized a part of the visiting scientist's compensation provided by LPI to visit several universities (Washington Univ., St. Louis; Univ. of Calif., San Diego and California Inst. of Technology), primarily to discuss and get feedback on the work on SEP production of short-lived nuclides I have been involved in (see Item-I). I gave seminar on this topic at each of these places and benefited immensely from very productive discussion sessions.

28th LPSC, Houston, 1997, p. 439-440

PRODUCTION OF SHORT-LIVED NUCLIDES BY SOLAR ENERGETIC PARTICLES IN THE EARLY SOLAR SYSTEM. J.N.Goswami[1,2], K.K.Marhas[2] and S.Sahijpal[2], [1] Lunar and Planetary Institute, Houston, Texas - 77058, USA, [2] Physical Research Laboratory, Ahmedabad - 380 009, India

Theoretical estimates for the production of the short-lived nuclides ^{41}Ca, ^{36}Cl, ^{26}Al, and ^{53}Mn by solar energetic particles have been made to check if the one time presence of these extinct nuclides in the early solar system could be attributed to their production in the nebula by energetic particles from an active early Sun. The results obtained in this study, coupled with the recent observation of correlated presence/absence of ^{41}Ca and ^{26}Al in refractory meteoritic phases [1], effectively rule out this possibility.

Several suggestions have been made to explain the presence of the short-lived nuclides ^{41}Ca, ^{36}Cl, ^{26}Al, ^{60}Fe, ^{53}Mn and ^{107}Pd in the early solar system (see [2] and references therein); these include: (i) injection of freshly synthesized stellar material to the solar nebula, (ii) "fossil" remnants locked in stardust present in the nebula and (iii) production by energetic particles either from stellar sources within a molecular cloud complex or from an active early Sun. Most of the studies done so far on the production of these nuclides by solar energetic particles (SEP) [3-6] are inadequate as they have made ad-hoc assumptions regarding the energy spectra of SEP, considered production of only ^{26}Al, ignored production by alpha particles and did not consider all the possible proton induced reactions of interest. Wasserburg and Arnould [7] incorporated alpha particle induced reactions and did a detailed calculation on the production of ^{26}Al and ^{53}Mn and found that co-production of these two nuclides by SEP to match meteoritic observation appeared to be unlikely. The recent evidence for the presence of the short-lived nuclide ^{41}Ca in the early solar system [2,8] and the strong hint for the presence of ^{36}Cl [9], led us to make a detail analysis of possible production of these two nuclides along with ^{26}Al and ^{53}Mn by SEP from an active early Sun.

We consider both the standard representations of the SEP spectra, a power law in kinetic energy (dN/dE = const. $E^{-\gamma}$) and exponential in rigidity (dN/dR = const. exp[-R/R_0]). The spectral parameters γ and R_0 are assigned values of 2-5 and 50-400, respectively, which cover a wide range of spectral shapes including those seen in contemporary flares [10, 11]. The alpha particle to proton ratio was kept variable; the results presented here are for a value of 0.1 for this ratio. The cross-sections for the reactions of interest have been taken from the recent compilation by Ramaty et al. [12] for ^{41}Ca, ^{26}Al and ^{53}Mn. Measured cross sections for ^{36}Cl are not available, and we have considered nuclear reaction systematics in this mass region to obtain reasonable estimate of reaction cross sections of interest. We have considered CAI precursor nebular dust as the target material. They are assumed to be of CI composition with sizes in the range of 10μm to millimeters following a size distribution of the type: dN/dR = const. $R^{-\alpha}$. It may be noted that the coarse-grained CAIs, in which most of the fossil records for the presence of ^{26}Al and ^{41}Ca have been found, are devoid of solar flare heavy nuclei tracks and direct irradiation of CAIs by SEP can be ruled out. Further, the strong hint for the presence of ^{36}Cl in the early solar system comes from analysis of matrix material of a CV3 chondrite [9].

We assume the nebula to be transparent to the SEP, consider only ionization energy loss of the particles and follow the approach of Lal [10] to obtain the energy spectra of the SEP at different depths within a grain and evaluate production rates as a function of depth in grains of different sizes. The production depth profiles are then used to obtain the average production rate as a function of grain size. Using an analytical expression to represent the relation between production rate and grain size, we obtain the ensemble average production rates for different grain-size distribution with $\alpha \geq 3$. All the calculations are based on the following flux normalization : N(E>10MeV) = 100 protons $sec^{-1}.cm^{-2}$, which fairly well represents the long-term averaged SEP flux based on lunar sample data [13].

Based on the production rates for the different nuclides obtained in this study, we infer the flux enhancement factor, over the long-term averaged SEP flux noted above, necessary to match the meteorite data for the initial abundance of these nuclides in the early solar system. The initial abundance ratios considered by us are: $^{26}Al/^{27}Al = 5\times10^{-5}$ [14], $^{41}Ca/^{40}Ca = 1.4\times10^{-8}$ [2], $^{36}Cl/^{35}Cl = 1.4\times10^{-6}$ [9] and two values for ^{53}Mn/^{55}Mn, 4.4×10^{-5} [15] and 7×10^{-6} [16], respectively. The required enhancement factor in SEP flux as a function of irradiation duration is shown in Fig. 1 for spectral index $\gamma = 3$ and $R_0 = 100$MV, respectively. It is obvious from the results shown in this figure that no irradiation time/enhancement factor combination can lead to co-production of ^{26}Al with any of the other three nuclides that will match the meteorite data. This is also true for the results obtained using the other values of spectral parameters considered by us. Co-production of ^{41}Ca, ^{36}Cl and ^{53}Mn (the higher initial) appears to be likely if the enhancement factor is $>10^4$ and the irradiation time scale is close to a million years; the enhancement factor will be higher for shorter irradiation duration. More importantly, the lower initial value for ^{53}Mn/^{55}Mn can be

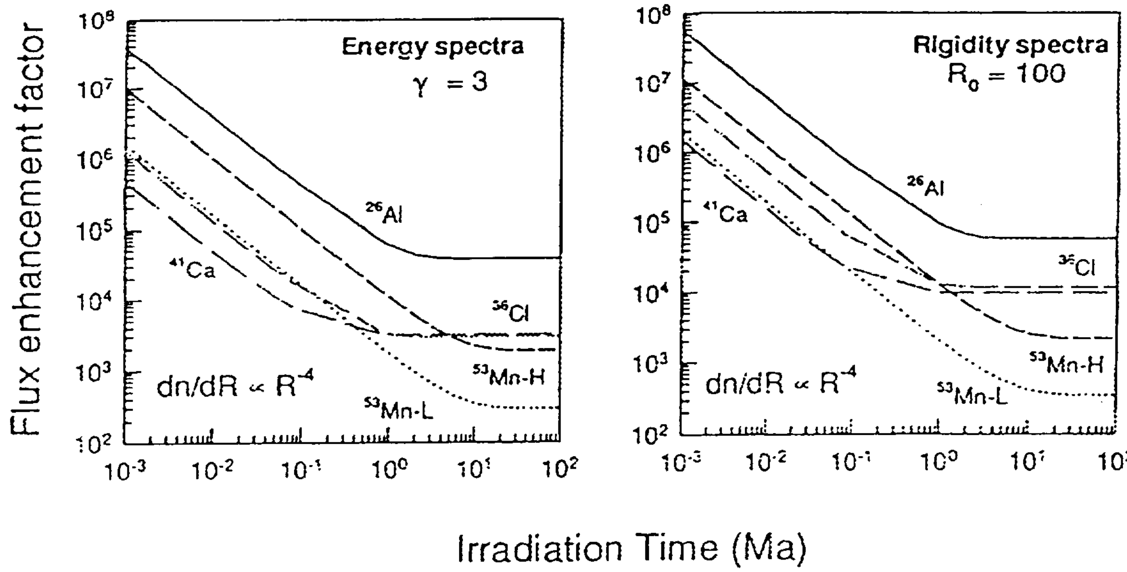

Fig. 1. Flux enhancement factor for SEP from the early Sun necessary for the production of the short-lived nuclides ^{41}Ca, ^{36}Cl, ^{26}Al and ^{53}Mn to match their abundances in the early solar system (as inferred from meteorite data), plotted as a function of irradiation duration for two spectral representation of SEP and a grain size distribution $dN/dR \propto R^{-4}$. The two values for initial ^{53}Mn/^{55}Mn ratios are labelled ^{53}Mn-H and ^{53}Mn-L, respectively.

generated even with a much lower enhancement factor for similar irradiation duration. The enhancement factors shown in this figure should be considered as lower limits as we have not considered the radial gradient in SEP flux; note that the reference flux based on lunar sample data is for irradiation at 1AU space, while the irradiation of the meteoritic phases most probably took place at a distance of 2-4AU from the Sun.

Enhancement in SEP flux from an active early Sun has been proposed to explain the observed excess of cosmogenic ^{21}Ne in solar flare irradiated olivine grains from CM chondrites [17]. These data suggest enhancement factors of ~100 to 1000, that are much lower than the values needed to explain the short-lived nuclide data. One may postulate that the enhancement factor could have been much higher at the time of irradiation of the CAI precursor solids which must have preceded the irradiation of the CM olivines. However, a crucial piece of new evidence that effectively rule out SEP production of ^{41}Ca and ^{26}Al is the correlated presence/absence of these two nuclides in meteoritic phases [1] indicating them to be co-genetic. Since co-production of these two nuclides by SEP is not possible (this is also true for energetic particle irradiation in a molecular cloud complex [12]), we can rule out irradiation scenario of any kind for the production of these two nuclides. SEP Production of ^{36}Cl also appears to be unlikely. If the lower value for the initial ^{53}Mn/^{55}Mn ratio is confirmed by further experiments, SEP production of ^{53}Mn present in the early solar system could indeed be possible.

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